Investigating the effects of laser intensity and pulse duration on 6.7-nm BEUV emission from Gd plasmas

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1. Introduction

- Gd^{12+} to Gd^{27+} transitions identified to emit at 6.7 nm for electron temperatures > 100 eV [1]
- Same transition array that is responsible for emission at 13.5 nm in Sn plasmas [1 - 5]
- Conversion efficiency (CE) around 0.3% [6] reported in 0.6% band-width of available La/B_4C multi-layer mirrors
- In experiments we investigated the influence of both laser intensity and pulse duration on emission from laser-produced Gd plasma
- EUV emission and ion time of flight (TOF) is optimised, for developing a viable and efficient next generation lithography source
- At certain laser intensities, an increase in CE was observed with a corresponding increase in ion TOF

2. Experimental set-up

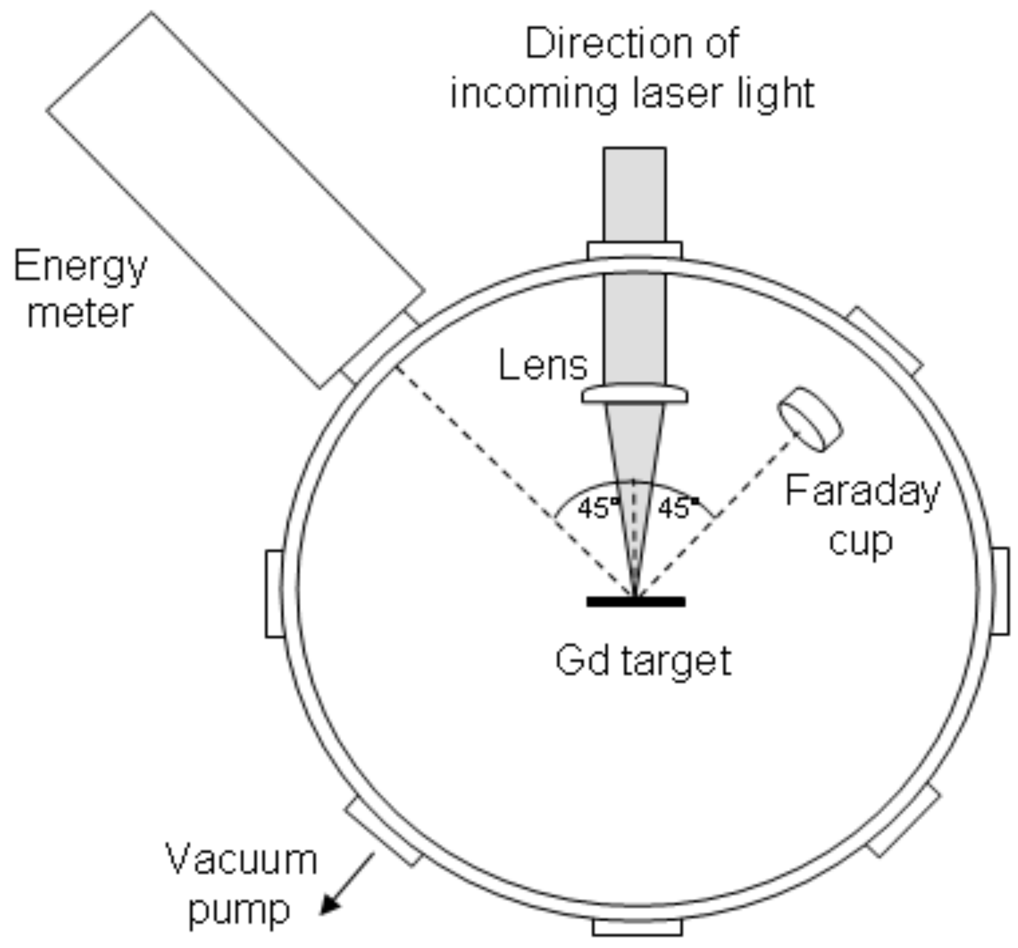

Figure 1: *Schematic of experimental set-up*

Laser systems parameters

	τ	λ	E_{max}
Nd:YAG	**10 ns**	**1064 nm**	**420 mJ**
Nd:YAG	**150 ps**	**1064 nm**	**210 mJ**
Ti:sapphire	**140 fs**	**800 nm**	**30 mJ**

- Laser intensity range: 10^{11} - 10^{15} W/cm^2
- CE - EUV energy monitor consisting of two molybdenum boron carbide (Mo/B4C) mirrors and a zirconium (Zr) filter, was oriented at 45° to the target normal
- TOF - Faraday cup placed at 45°, at a distance of 10 cm with a bias of -17 V applied

3. Results

- A maximum CE of 0.4% recorded. Corresponding to 1.3% for comparison with Sn
- Optimum CE observed for laser intensity of 7x10^{13} W/cm^2 using ps Nd:YAG laser
- Improved CE due to higher plasma temperature
- Higher intensities of fs pulse leads to overheating of the plasma, leading to a less efficient EUV emission process

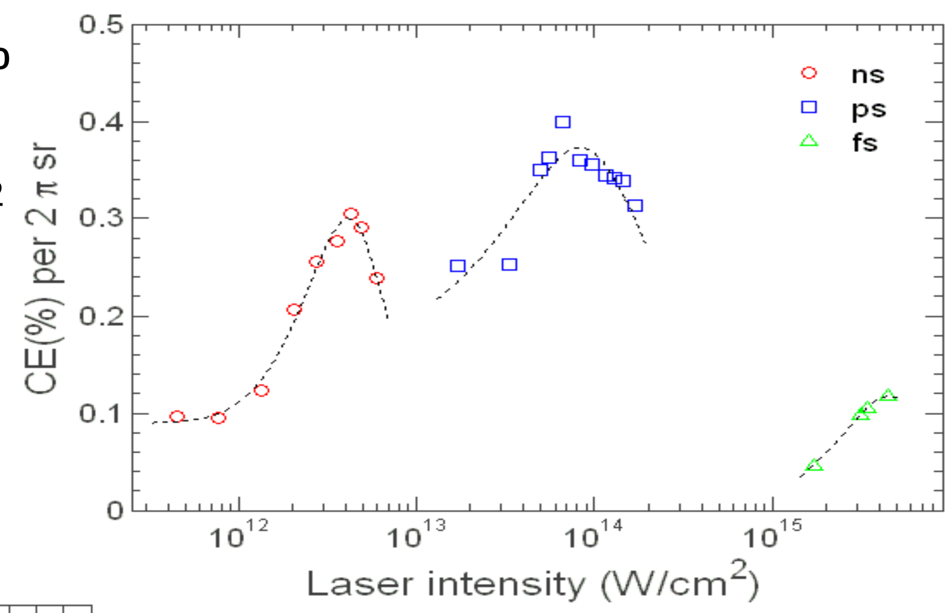

Figure 2: *CE results for ns, ps and fs*

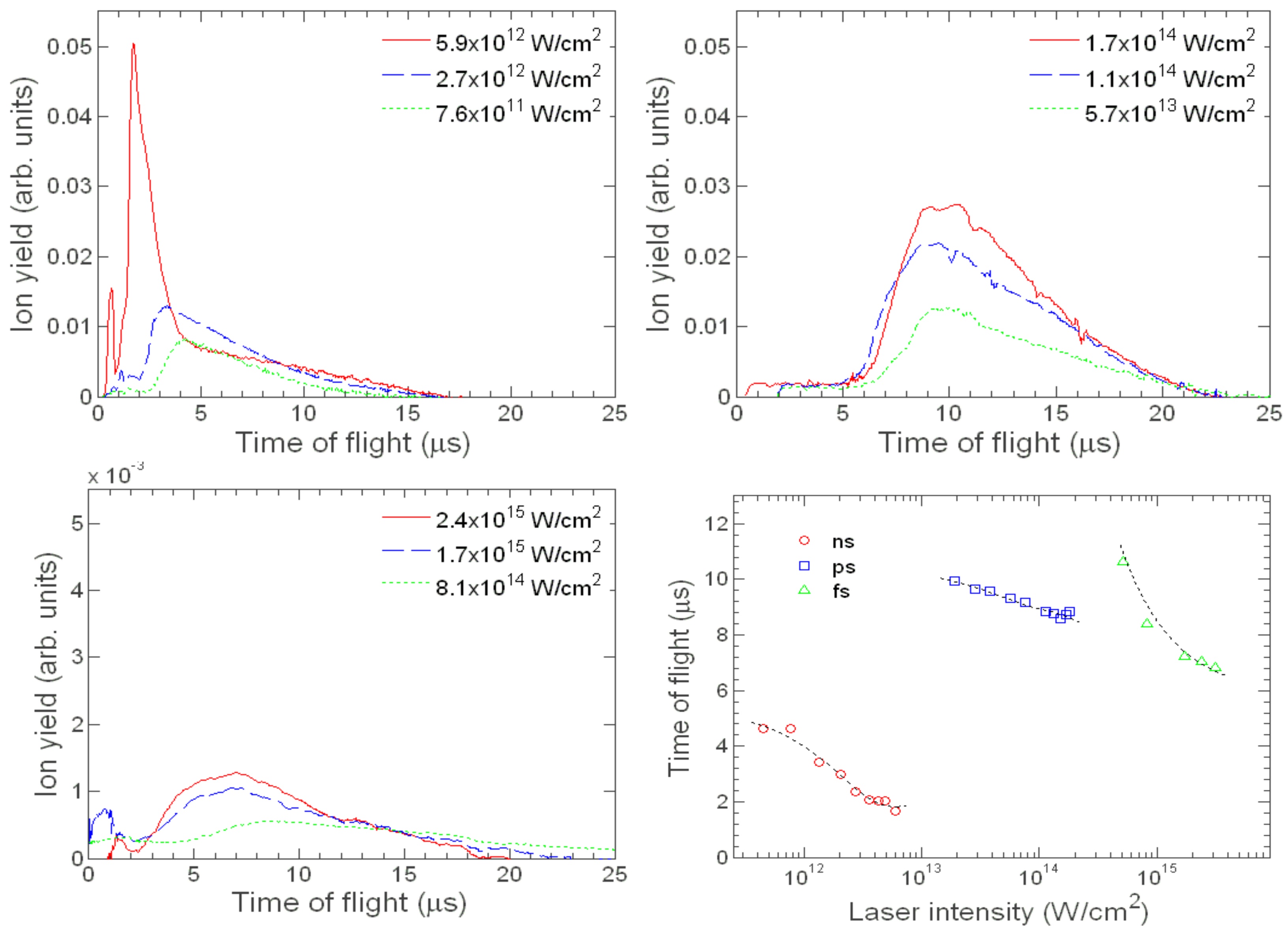

Figure 3: *TOF signals of each laser (a), (b) and (c) for various laser intensities and (d) a plot of TOF v Laser intensity.*

- The ion yield at time corresponding to signal peak was lower for ps than ns laser irradiation
- Shorter pulse duration forms a smaller plasma. Electrostatic field induced by formation of plasma [7] determines TOF and maximum ion kinetic energy
- This assists with debris mitigation and reduce damage to optical components by fast ion bombardment

- Fig. 4(a) shows electron temperature (*Te*) dependence on laser intensity by use of a simple one-dimensional hydrodynamic code
- According to the numerical simulation, *Te* is on the order of 130 eV at a laser intensity of 7×10^{13} W/cm^2 for the laser pulse duration 150 ps
- A steady-state collisional radiative model [8] calculated Gd ion populations as a function of the *Te*, as shown in Fig. 4(b)
- Results show Te should be tuned from 80 to 130 eV for strong 6.7-nm emission

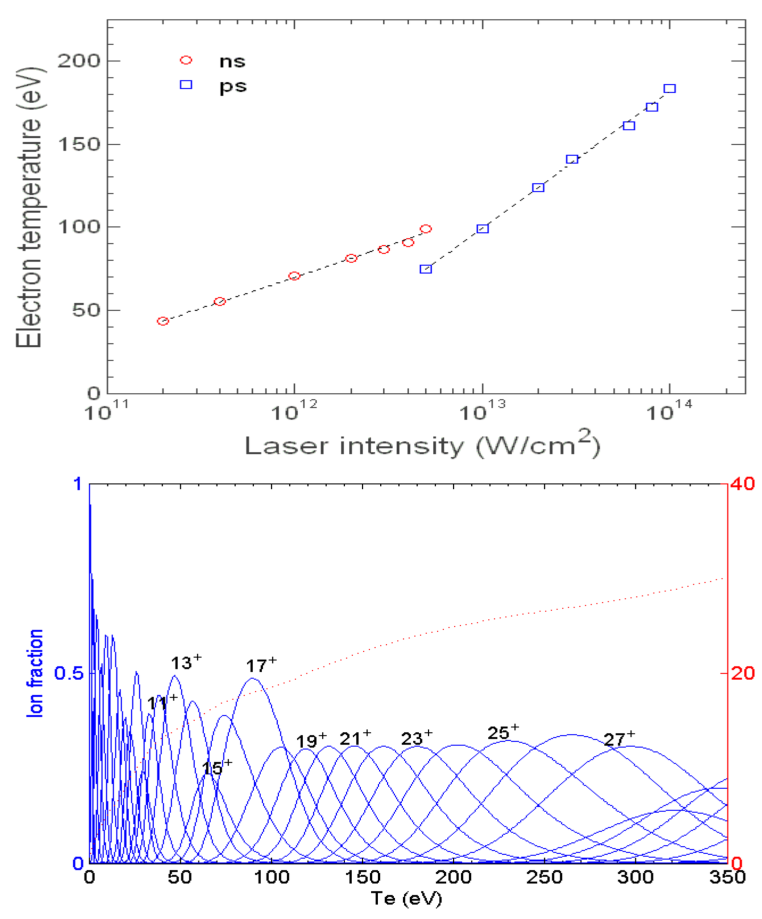

Figure 4: *(a) 1-D hydrodynamic simulation and below (b) CR model*

4. Discussion

- Maximum CE of 0.4% achieved with ps pulse at 7x10^{13} W/cm^2 laser intensity
- For this intensity, an ion TOF of 9 μs was observed
- At laser intensity corresponding to maximum CE from the ns laser, a TOF of 2 μs was recorded
- For a viable future lithography source this demonstrates ps irradiation gives both an increase in CE and reduced fast ion bombardment
- Modeling work shows good agreement. An intensity of 7x10^{13} W/cm^2 predicted an *Te* of around 130 eV. The CR model confirmed the transitions for EUV emission from Gd occur around this temperature
- Source not optimal as EUV emission suppressed due to optically thick plasma
- Future work involves the use of ps CO_2 LPP or mass limited targets for improved opacity effects

5. References

[1] D. Kilbane and G. O'Sullivan, J. Appl. Phys. **108**, 104905 (2010)
[2] S. S. Churilov, R. R. Kildiyarova, A. N. Ryabtsev, and S. V. Sadovsky, Phys. Scr. **80**, 045303 (2009)
[3] J. Sugar and V. Kaufman, Phys. Scr. **24**, 742 (1981)
[4] J. Sugar, V. Kaufman, and W. L. Rowan, J. Opt. Soc. Am. B **10**, 799 (1993)
[5] J. Sugar, V. Kaufman, and W. L. Rowan, J. Opt. Soc. Am. B **10**, 1321 (1993)
[6] T. Otsuka, D. Kilbane, T. Higashiguchi, N. Yugami, T. Yatagai, W. Jiang, A. Endo, P. Dunne, and G. O'Sullivan, Appl. Phys. Lett. **97**, 231503 (2010)
[7] M. Murakami, Y.-G. Kang, K. Nishihara, S. Fujioka, and H. Nishimura, Phys. Plasmas **12**, 062706 (2005)
[8] D. Colombant and G. F. Tonon, J. Appl. Phys. **44**, 3524 (1973)

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